Modeling the Effects of Spacecraft Venting on Instrument Measurements of the Martian Atmosphere for an Elliptical Orbit

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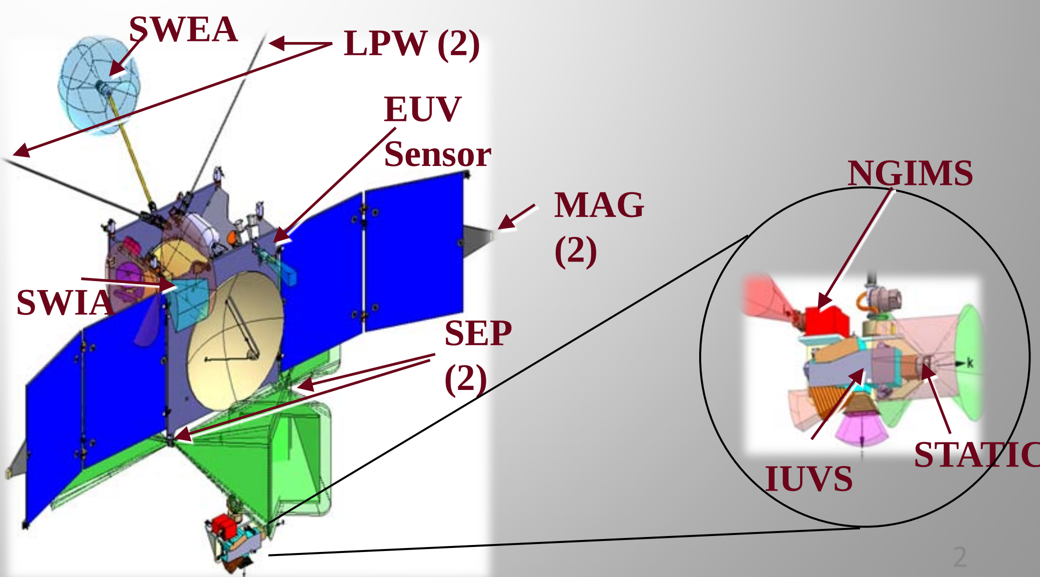
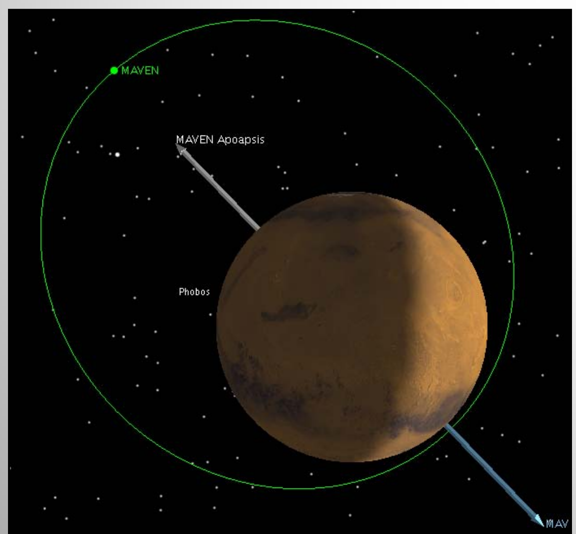
Background

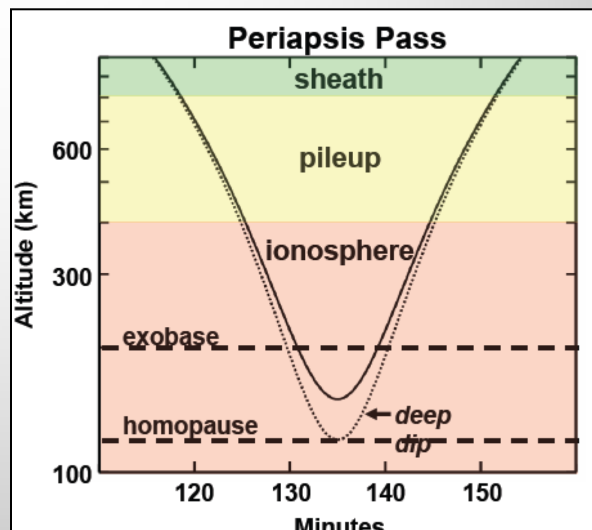
- Analysis performed for MAVEN mission
  - Will study the Martian atmosphere, ionosphere, and interactions with sun and solar wind
  - Emphasis on the loss of volatile compounds ($C0_2$, $N0_2$, H_20) from the atmosphere to space



Background

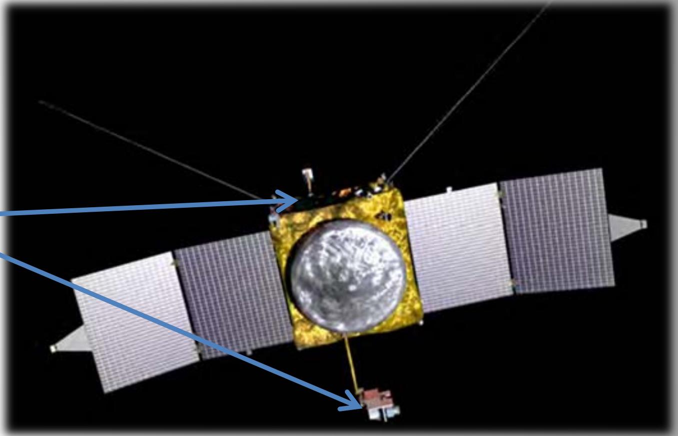
- Elliptical science orbits:
  - Nominal: 150 km x 6220 km altitude with 4.5 hour period
  - 'Deep Dip': Periapsis altitude lowered to 125 km to measure higher density regions
- Large pressure range (10^{12} Pa at apoapsis, 10^{6} Pa at nominal periapsis, 10^{5} Pa at Deep Dip periapsis)





Background

- With large pressure variations in orbit, need to understand how internal pressures change
- Internal pressures may track but also lag atmospheric pressure
- Flux of gas from vents could potentially bias instrument measurements



Goal: Predict the effect that atmospheric gases trapped and vented from spacecraft volumes could have on instrument measurements.

Approach

- Ambient Atmosphere
  - Determine properties throughout orbit
  - Analyze pressures on surfaces accounting for s/c orientation and velocity
- Flow Across Vents
  - Calculate molecular flow vent properties of all major volumes (instruments, spacecraft)
  - Perform transient flow across vents to predict pressures inside volumes
- Free Molecule
  - Predict redistribution of gases from vents with molecular transport analysis

Ambient Atmosphere

1. Orbit Prediction
2. Mars Atmosphere
3. Effective Pressures

Fluxes of **ambient gases**

Vent Flow

1. Vent Conductance
2. Mass Conservation ODE
3. FM Source Fluxes

Flow across vents

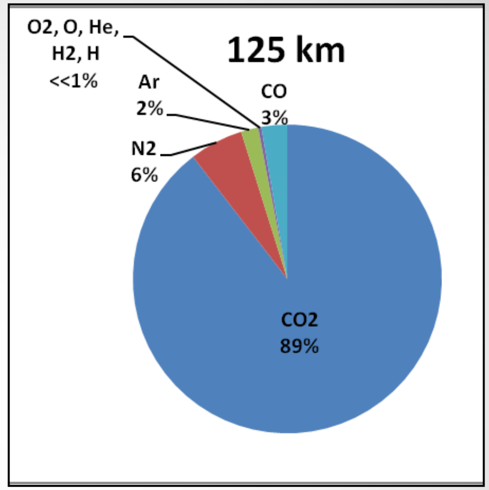
Free Molecule Transport

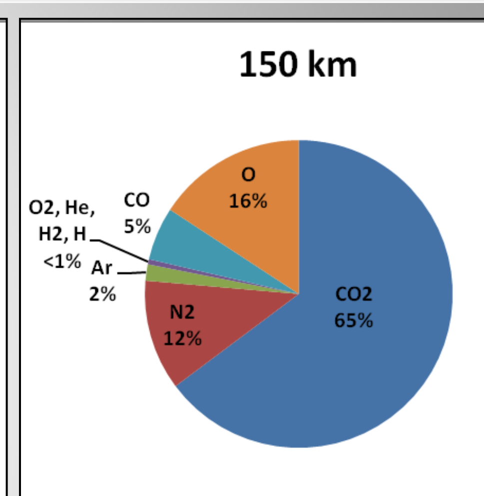
1. Direct Flux
2. Reflected Flux

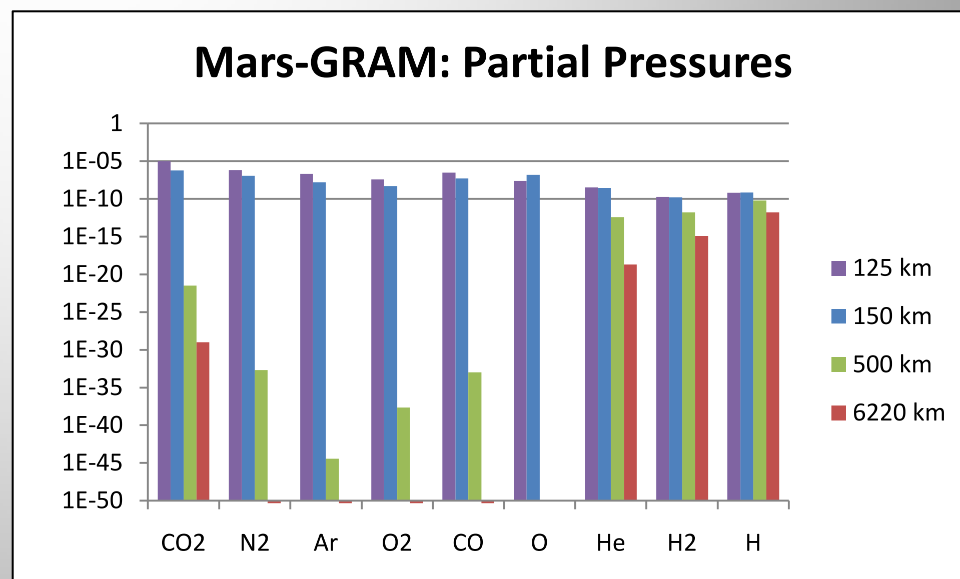
Fluxes of **vented gases**

Ambient Steps 1 & 2

- Orbit position prediction
  - Calculated using Keplerian orbital elements
    - a = 6578 km
    - e = 0.462
    - i = 75°
  - No perturbations
- Mars atmosphere
  - Mars Global Reference Atmospheric Model 2005 (Mars-GRAM)
    - Maintained by Marshall Space Flight Center
  - Used to calculate density and composition of ambient species

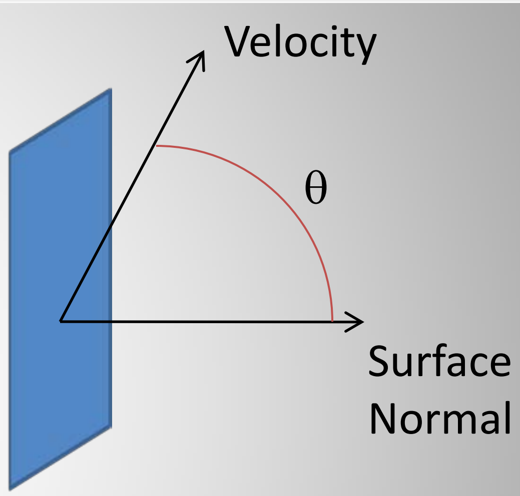






Ambient Step 3

- Effective pressures calculated for each element
  - Function of:
    - ambient density (ρ)
    - spacecraft velocity (v)
    - average molecule velocity (u)
    - element surface to flow angle (θ)
  - Incorporated new 'ram impingement' mass flux model [1]:
    - Velocity scale factor (s)
    - Mass flux calculated using scale factor



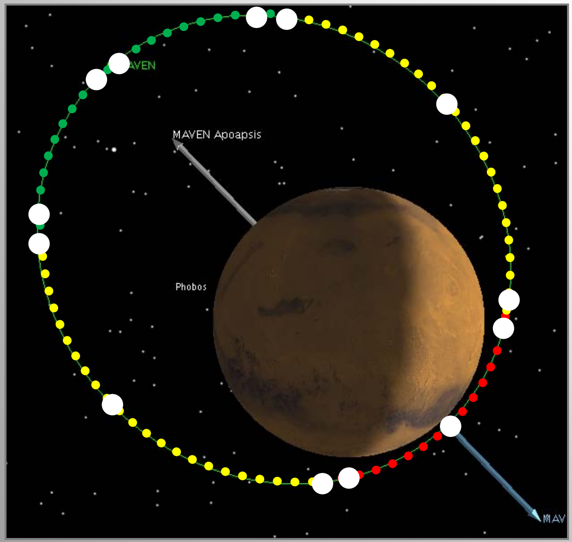
$$s = -\frac{v}{u}\cos\theta$$

$$\dot{m} = \rho u \sqrt{\frac{1}{4\pi}}\left(e^{-s^2} + \sqrt{\pi}\left[1 + erf(s)\right]\right)$$

[1]J. Borde, P. Renard, G. Sabbathier, G. Drolshagen, "Improved Analysis Tool for the Computation of Spacecraft Surface Erosion Due to Atomic Oxygen," *Proceedings of the Sixth International Symposium on Materials in a Space Environment*, **271,** ESTEC, Noordwijk, The Netherlands, 19-23 September 1994.

Effective Pressure Calculations

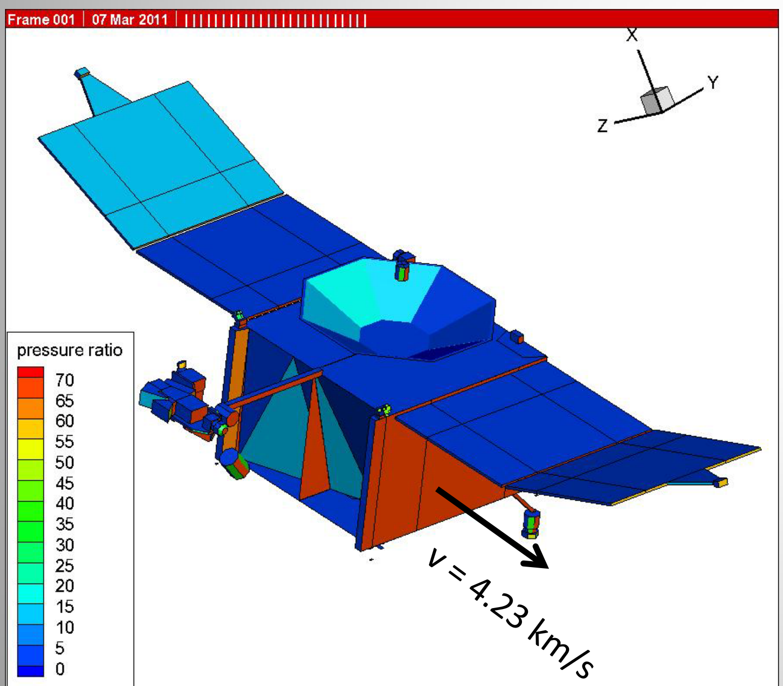
- ‘Effective pressures’ calculated for 13 discrete points in orbit
  - Atmospheric density and spacecraft orientation vary
  - Sum of direct flux of impinging atmospheric molecules and reflected flux off spacecraft surfaces



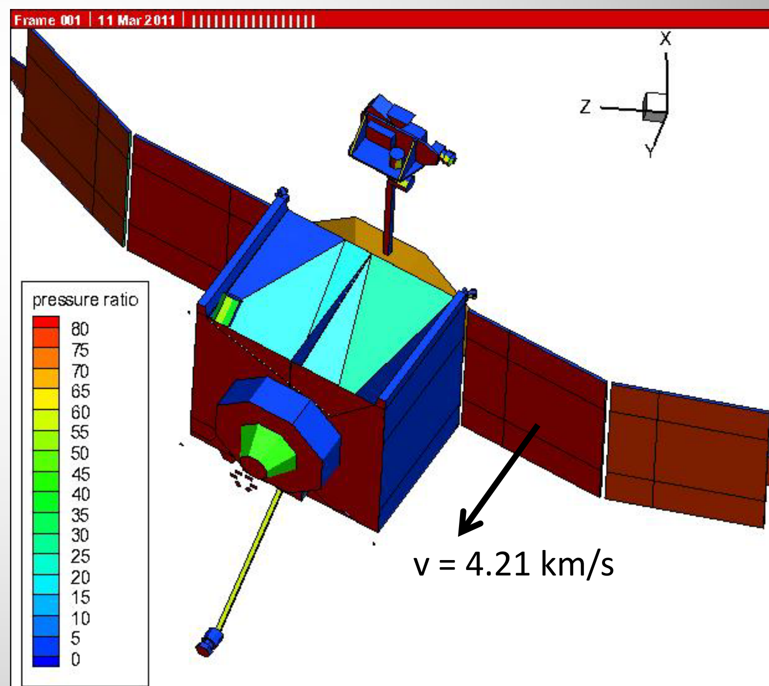
Orbit Segment	Possible Orientations
Below 500 km (Deep Dips)	**“Fly – Z”**
Below 500 km (nominal)	**“Fly – Y”** Sun Velocity
500 km – 5200 km (sides)	**Sun Nadir** Sun Inertial
Above 5200 km (apoapse region)	**Sun Inertial**

Effective Pressure Results

- Ratio of effective pressure to ambient pressure shown below for periapsis of nominal orbit (left) and Deep Dip (right)
  - Max effective pressures about 70x ambient (150 km) and 80x ambient (125 km)



Effective Pressure / Ambient Pressure
(150 km)



Effective Pressure / Ambient Pressure
(125 km)

Flow Calculations (Step 1)

- Depressurization time constant (τ) used to compare efficiency of different vents:
  - Time for ΔP to drop by factor of e
  - Function of inner volume (V) and vent conductance (C)
- Conductance (C) is a measure of the ease at which gases flow through a duct
  - Analytical solutions available for simple vents
  - Complex geometries require numerical solution

Time constant:

$$\boxed{\tau[s] = \frac{V[m^3]}{C[m^3/s]}}$$

Circular tube of constant cross section:

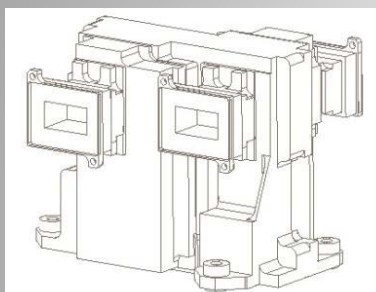
$$\boxed{C = \frac{2\pi R^3 v}{3L} \cdot K''}$$

Multiple vents in parallel:

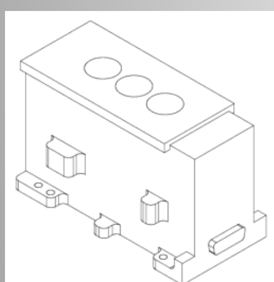
$$\boxed{C_{eq} = C_1 + C_2 + \ldots + C_N}$$

Sample Vent Geometries

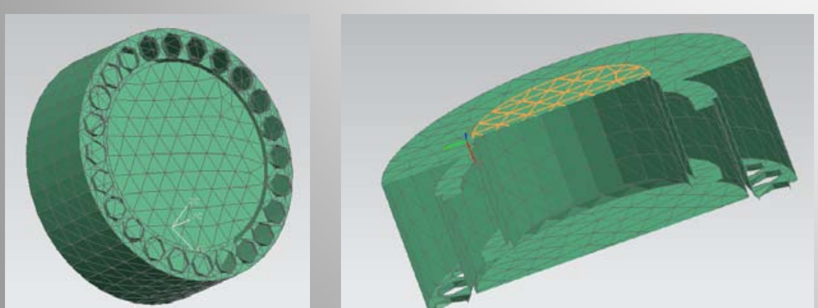
- Various instrument



4 identical baffles
(tapered rectangular tubes in parallel)



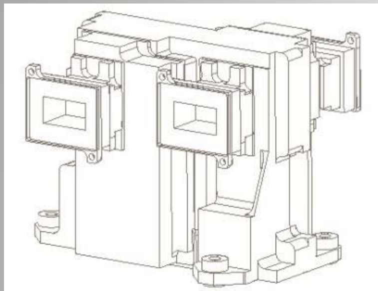
3 aperture holes
(short circular tubes in parallel)



Labyrinth vent
(GBVF analysis)

Sample Vent Geometries

- Various instrument vents:



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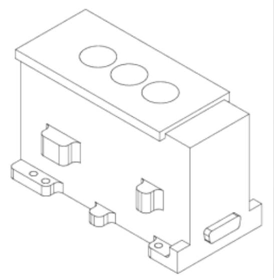

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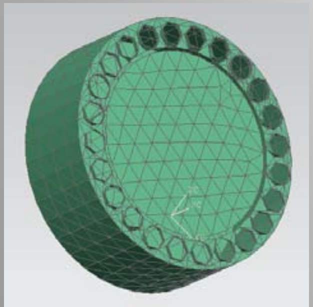
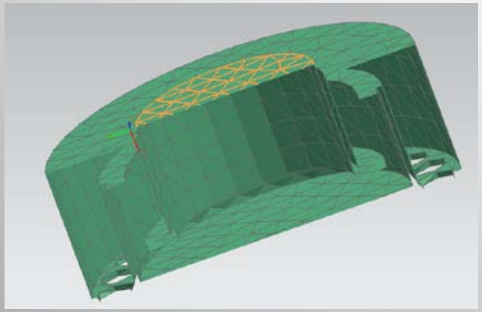




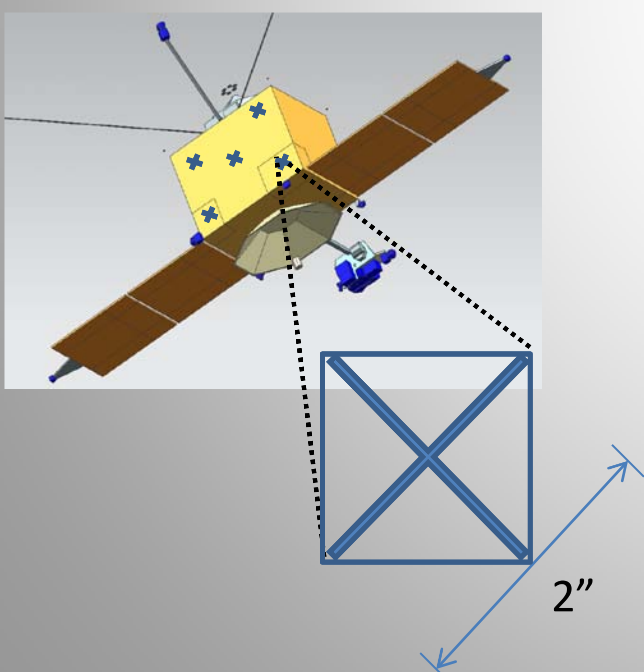
Labyrinth vent
(GBVF analysis)

- Labyrinth vent required gray body viewfactor (GBVF) analysis
  - Set the entrance and exit sticking coefficient to 1, all others to zero
  - GBVF solved using Gebhart's method (matrix inversion)
  - GBVF from entrance to exit is the <u>transmission probability</u> (k)
  - Conductance of a tube is aperture conductance times transmission probability:

$$\boxed{C = \left(\frac{1}{4} vA \right) (k)}$$

Vent Comparison

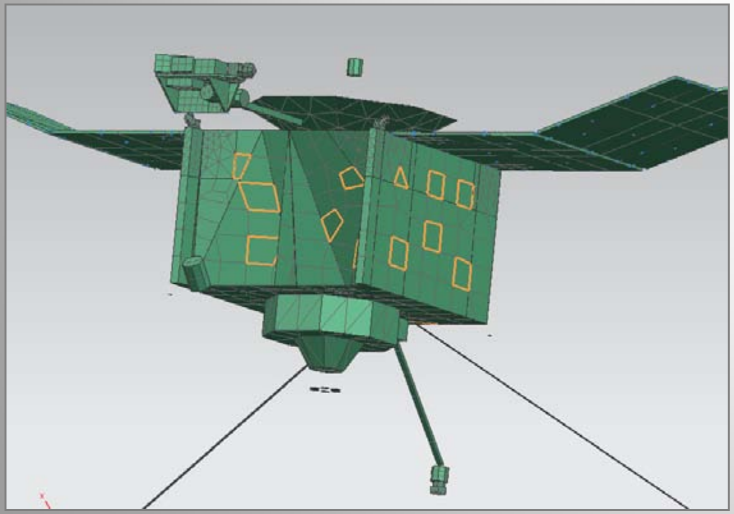
- Time constants (volume/conductance) compared for 11 instrument vents and spacecraft bus vents
  - Spacecraft bus venting found to be limiting case
    - S/C provider using 2x2” x-cuts in MLI to vent bus interior (24 cuts assumed)
    - Assumed cut width of 1/16”, MLI thickness of 1/4"



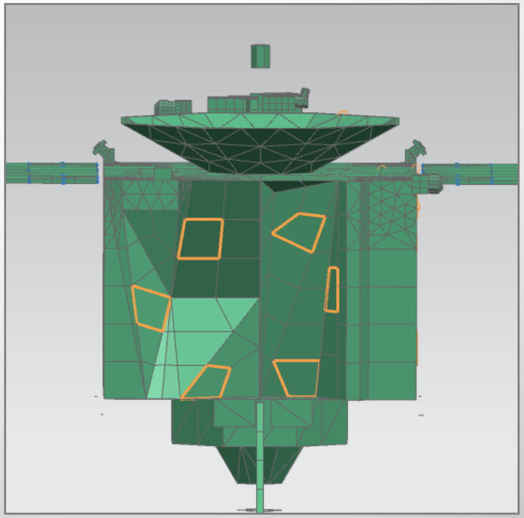
Component	Open Volume (m^3)	Conductance (m^3/s)	Time Constant (s)
Spacecraft Bus Vents			
Spacecraft Bus [1]	4.46	0.15	**29**
Instrument Vents			
IUVS	8.35e-2	0.023	0.4
NGIMS	4.36e-3	0.003	**3.0**
RSDPU	5.41e-3	0.00076	**2.0**
SWIA/SWEA/STATIC Aperture	1.34e-4	1.8e-5	**7.4**
SWIA/SWEA/STATIC Electronics	1.9e-3	0.0012	**1.6**
SEP [3]	4.16e-4	0.042	0.01
MAG	3.69e-4	0.0017	0.21
EUV	7.67e-4	0.73	0.01
LPW (Pre-amps)	1.74e-5	0.0004	0.04
LPW (Stacers)	1.74e-4	0.11	0.002

FEM and Vent Placement

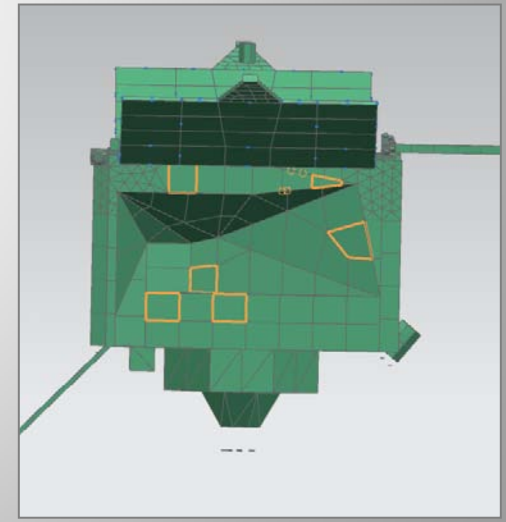
- 24 vents were divided evenly between 4 lateral faces (+X, -X, +Y, -Y)
- Elements selected to represent vent locations (spread out across face)



+X and +Y vent locations



-X vent locations



-Y vent locations

Flow Calculations (Step 2)

- Solved for pressure inside spacecraft bus at each time step
  - Transient ambient pressures on the vent FEM elements used as boundary conditions to solve gas flow differential equation:

$$V\frac{dP}{dt} = C(\Delta P)$$

- Solved separately for each species
  - Travel independently of one another in molecular flow regime
- Solved in log scale of pressure to avoid negative numbers (pressure boundary condition had dynamic range of 1e-5 to 1e-70)

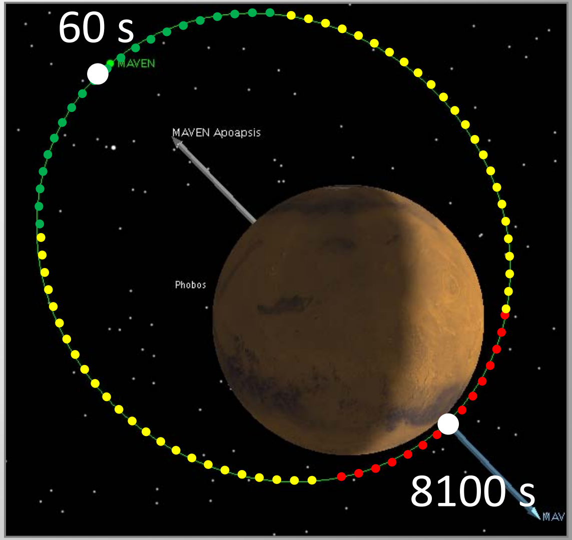
$$\frac{d(\ln P)}{dt} = \frac{1}{P}\frac{dP}{dt}$$

Step 2 Results

- Tracking each species independently gave composition of gas interior and exterior to bus

Time since Apoapsis (sec)	Altitude (km)	Internal Bus Pressure (Pa)	Atmospheric Pressure (Pa)	Bus/Amb % Comp Ratio CO_2	Bus/Amb % Comp Ratio He	Bus/Amb % Comp Ratio H
60	6220	1.5e-11	1.7e-12	1.00	1.00	1.00
1350	6025	9.2e-12	1.4e-12	0.94	1.00	1.00
1575	5950	1.0e-11	1.6e-12	0.97	0.998	1.00
4050	4425	3.1e-11	4.4e-12	0.96	0.91	1.00
6750	1250	7.1e-10	4.0e-11	0.59	0.98	1.00
7425	475	2.2e-09	1.9e-10	0.99	1.00	1.00
8100	150	2.1e-05	9.8e-07	1.00	0.96	0.96
8775	475	5.8e-09	2.3e-10	1.06	1.00	0.999
9450	1250	3.1e-09	1.9e-10	0.58	0.90	1.02
11925	4215	3.5e-11	4.4e-12	1.00	0.97	1.00
14625	5950	1.4e-11	2.1e-12	0.98	0.999	1.00
14850	6025	8.1e-12	1.7e-12	0.96	1.00	1.00
16200	6220	1.0e-11	1.3e-12	1.00	1.00	1.00

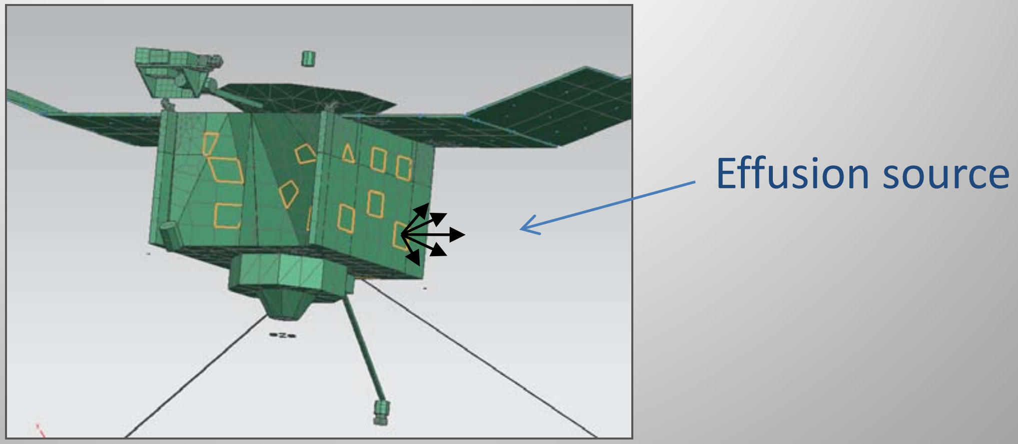
$$Ratio(species) = \frac{\left(\frac{Partial\ Pressure\ (species)}{Total\ Pressure}\right)_{bus}}{\left(\frac{Partial\ Pressure\ (species)}{Total\ Pressure}\right)_{ambient}}$$



Largest composition deviation, but how much of this gas actually makes it to the instrument apertures?

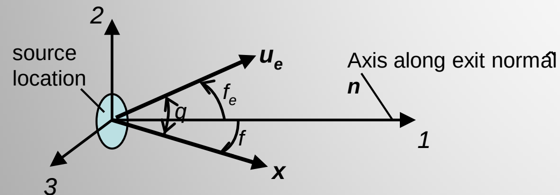
Flow Calculations (Step 3)

- Determine Free Molecule source terms
  - Used pressure inside spacecraft to determine flux through the vents to the outside
  - Did not use external pressure: inward flow is independent of outward flow in the free molecule regime
  - Converted to mass flux and treat as effusion source (Lambertian distribution, thermal velocity)



Free Molecule Calculations

- Direct Flux
  - Use solution of Boltzman equation to calculate gas flux to surfaces with a line of sight to the vents
  - M. Woronowicz, *Rarefied Gas Dynamics: 22nd International Symposium*, AIP, **585**, Melville, NY, 2001, pp. 798-805



$$\frac{\partial f}{\partial t} + \boldsymbol{v} \cdot \frac{\partial f}{\partial \boldsymbol{x}} = Q_1;$$

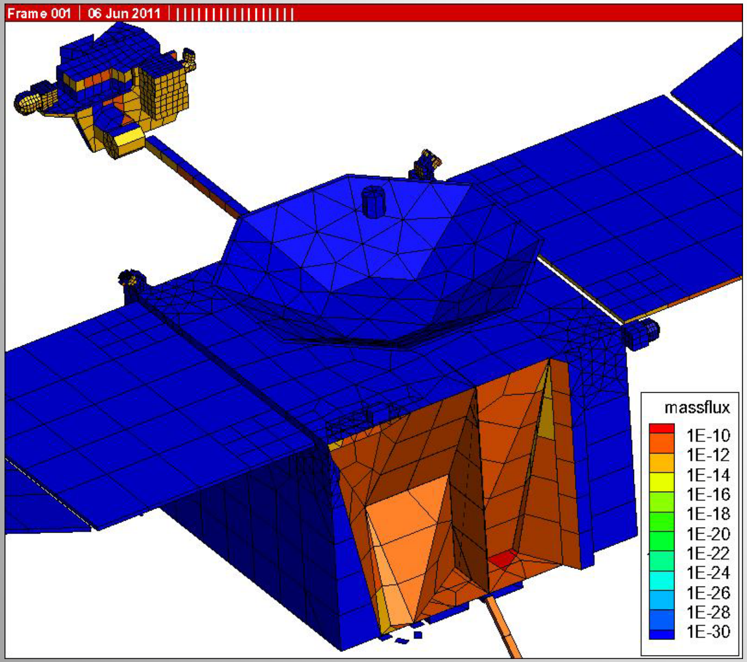
$$Q_1 = \frac{2\beta^4}{A_1 \pi} \delta(\boldsymbol{x}) \dot{m}(t) (\boldsymbol{v} \cdot \hat{\boldsymbol{n}}) \exp\left(-\beta^2 (\boldsymbol{v} - \boldsymbol{u}_\mathrm{e})^2\right);$$

$$A_1 \equiv e^{-s^2 \cos^2 \phi_\mathrm{e}} + \sqrt{\pi}\, s \cos\phi_\mathrm{e} \left(1 + \mathrm{erf}\,(s \cos\phi_\mathrm{e})\right).$$

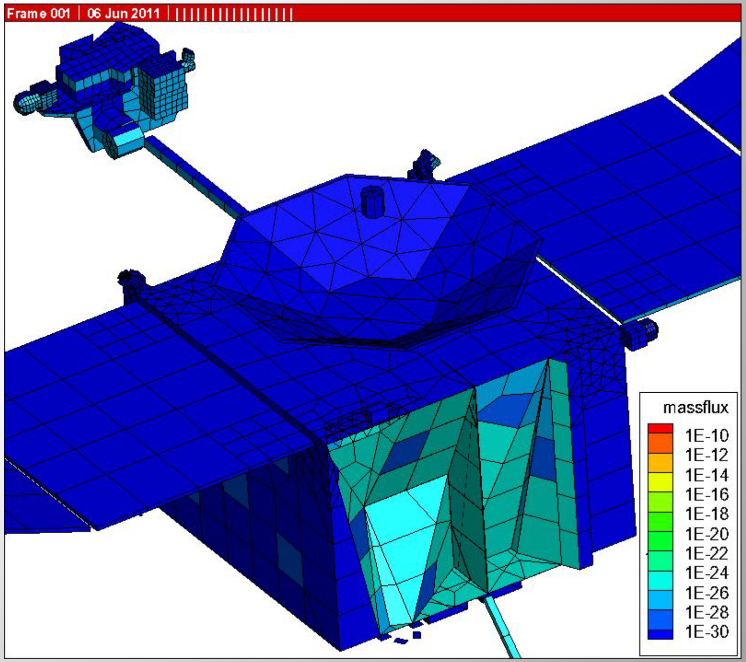
- Reflected Flux
  - Assume that all of the flux reaching a surface is reflected
  - Treat as a new effusion source
  - Add contributions to FEM elements to approximate the molecular transport solution
- Limitation of method
  - Does not account collisions between reflected and incoming molecules
    - Possible reduction in what reaches the surface
  - Did not repeat iteration to extend “view” to surfaces requiring more than one bounce to reach

Free Molecule Results

- Direct Flux
  - Max value is 10^{-10}
- Reflected Flux
  - Max value is 10^{-25}



$C0_2$ @ 125 km - Direct

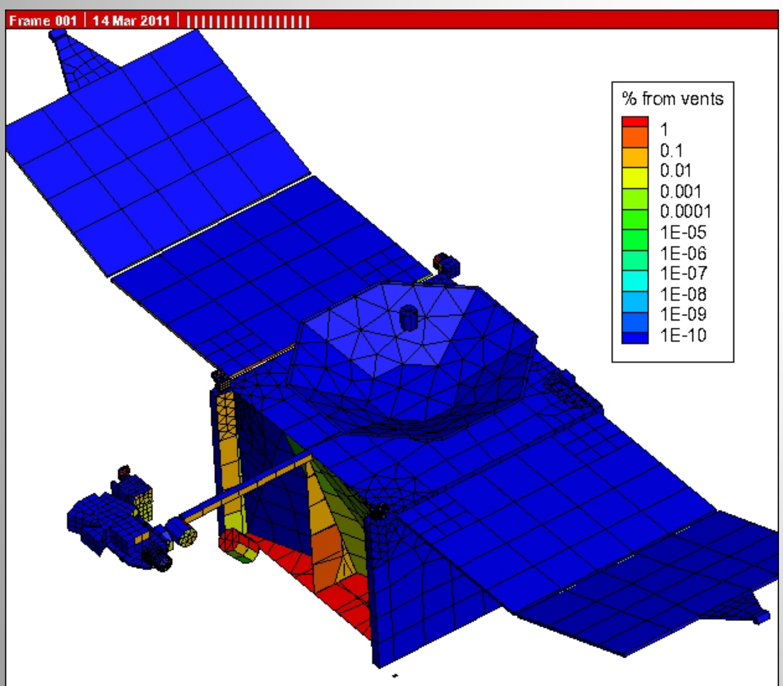


$C0_2$ @ 125 km – One Reflection

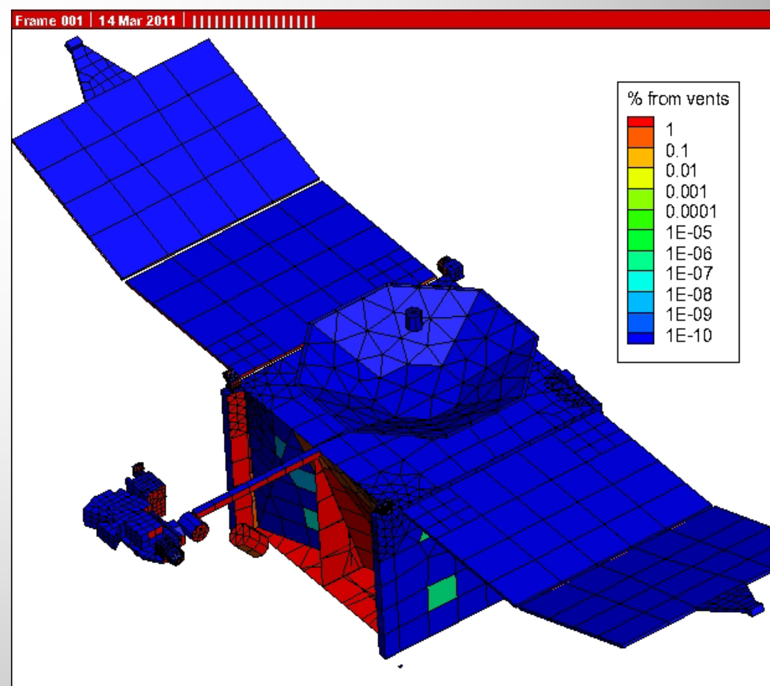
Analysis of Results – Deep Dip Orbit

- Spacecraft colored by percent of impinging flux originating from vented gas
  - Project interested in amount **relative** to atmospheric flux

$$\% = \frac{\Phi_{\mathrm{vent,in}}}{\Phi_{\mathrm{vent,in}} + \Phi_{\mathrm{amb,in}}} \text{ x } 100\%$$

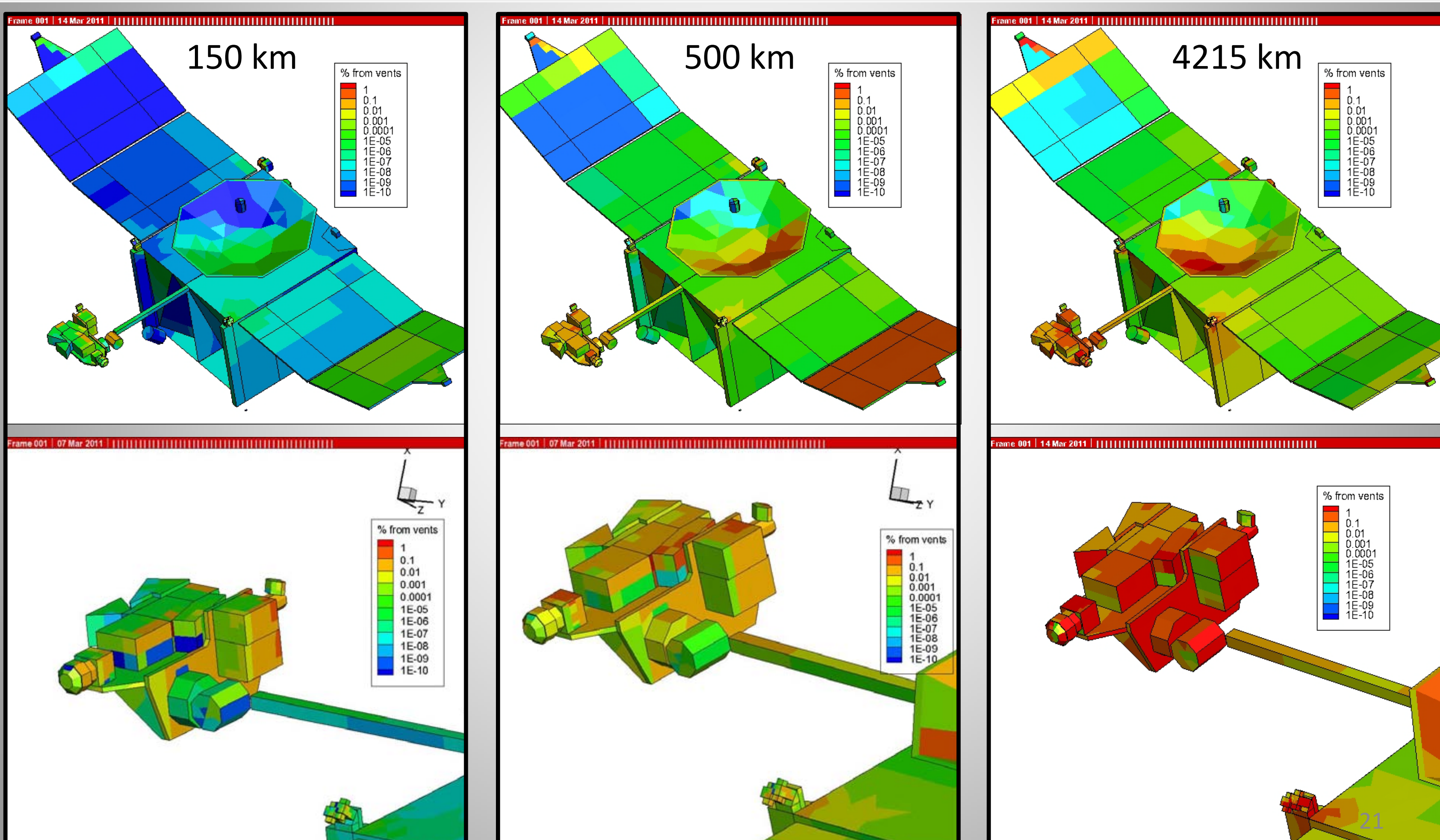


125 km (periapsis)



500 km (traveling out)

Analysis of Results – Nominal Orbit



Conclusions

- Analysis required unique implementation of direct/reflect flux and pressure calculation methods
  - Able to prove that vented gas does **not** pose a serious threat to instrument measurements for MAVEN
- For similar analysis in future:
  - Would implement spacecraft slew in Nx calculations (more automated)
  - Would incorporate shadowing from other surfaces in ram pressure calculations

Thank you!